Chapter 2

Experimental Details

2.1 Neutron Facility (14 UD Pelletron-Linac Accelerator at BARC-TIFR)

Accelerators are devices that accelerate charged particles using an electric field and magnetic field to focus them on beams. They are primarily used for applications that are commercial and medical. The 14 UD BARC-TIFR Pelletron Linac Facility, situated at TIFR in Mumbai, India is a 14 million-volt electrostatic tandem accelerator capable of accelerating particles such as protons, alpha particles, and different types of heavy ions at sufficiently high energies. The accelerator is mounted vertically in an insulating tank with a length of 25 meters and a diameter of 5.5 meters, which is filled with insulating SF_6 gas at a pressure of 6 to 7 bar to prevent electrical discharge of the high voltage terminal. The schematic diagram of the accelerator is shown in Fig. 2.1. The ion source at the top produces the negative ions. There are three different types of ion sources available, which are: (i) RF Charge Exchange Ion Source (Alphatross) (ii) MCSNICS, and (iii) Direct Extraction Negative Ion Duoplasmatron. Among these MCSNICS (Multi Cathode Source of Negative Ions by Cesium Sputtering) is commonly used for ion production. These negative ions are pre-accelerated to~300 KeV by the deck potential and then focussed and mass analyzed using the 90^o injector magnet before injecting them into the low energy accelerating tubes. The injector magnet bends the ions by 90^o in a vertical direction down in the accelerating column. Inside the vertical accelerating tank, a high voltage terminal is located at the centre. This terminal can be charged to very high potential varying from 1 MV to 14 MV. A potential gradient is maintained through the tube from the top of the tank to the terminal and from the terminal to the bottom. There are twenty eight 1 MV modules 14 on either side of the terminal. The portion above the terminal is called the low energy section and the portion below the terminal is called high energy section. The injected ions get accelerated down toward the high voltage terminal in the middle. At the terminal, the accelerated negative ions pass through a stripper, which can be a very thin carbon foil or a small volume of gas. During this passage through this stripper, the negatively charged ions lose electrons and thus result in a distribution of

positive charges. This distribution depends upon the velocity of the ions. These positively charged ions now get repelled down towards the ground potential through the high energy accelerating tube. A second stripper assembly is in the high energy dead section. This will help in further stripping and yield a higher charge state and hence higher energy. The energy gained by the ions after emerging out of the accelerator is given by:

$$E = E_0 + V(q+1) \text{ MeV}$$

if only a single stripper is used, where E_0 is the energy gained from the ion source deck, V is the terminal potential and q is the charge state of the ion [1].

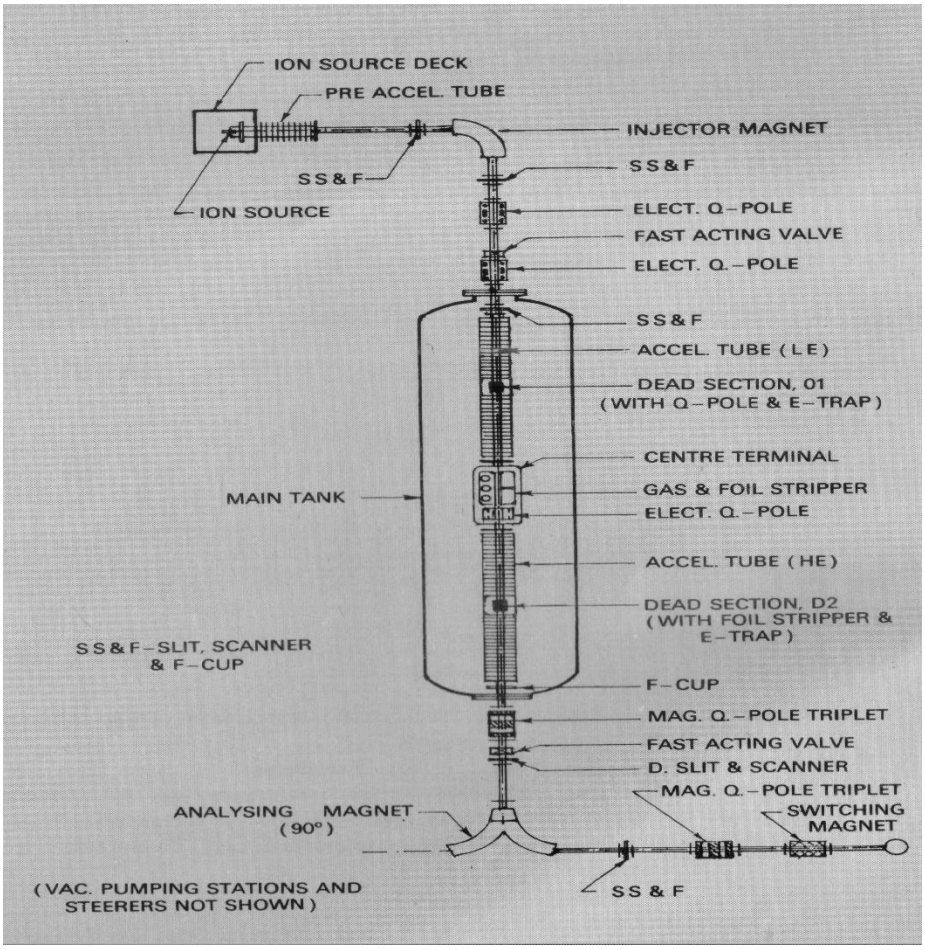

Fig. 2.1 *A schematic diagram of the BARC-TIFR Pelletron accelerator facility, Mumbai.*

2.2 Neutron source

The $^{7}\text{Li}(p,n)^{7}\text{Be}$ reaction is one of the most used nuclear reactions for accelerator based neutron sources. Natural lithium consists of isotopes ^{6}Li and ^{7}Li with abundances of 7.42 and 92.58 %, respectively [2]. The low threshold energy and high neutron yield make

this reaction favourable for such a purpose. However, lithium has a low melting point, and poor thermal conductivity, and is a highly reactive metal that forms compounds almost instantly when exposed to air. The thickness of the Li target is generally set so that incoming protons lose no more than a few MeV of energy. High energy neutrons from the ground state and first excited state of ^{7}Be, as well as lower energy neutrons from the excitation of additional beryllium states and continuum neutrons from break-up processes, are all included in neutron spectrum data. This neutron spectrum contains a low energy neutron tail along with the primary main neutron peak [3-4]. In addition, the neutron spectrum is satisfactory for applications such as cross section measurements for nuclear astrophysics and boron neutron capture therapy. Lithium is flammable when exposed to air therefore a specific assembly have been designed and used to handle such targets which can be directly installed at the 6M experimental port without exposing the hazardous materials to the users [5]. The neutron was produced via the $^{7}\mathrm{Li}(p,n)$ reaction (E_{th}=1.88 MeV) using the proton of 10, 13, 15, 16, 18, 19, 21 and 22 MeV energies. The average proton beam current was 180 nA during sample irradiation and proton energy spreads at 6M port elevation level (above analysing magnet) were 50-90 keV. A schematic view of the 6M irradiation set-up at BARC-TIFR is shown in Fig. 2.2. Initially, the proton was accelerated inside a 6 mm diameter collimator and hit on the natural lithium (Li) foil, which was sandwiched between the two tantalum (Ta) foil. The front tantalum foil which faced the proton beam is the thinnest one, whereas the proton beam stop was served by a thick layer of tantalum. The energy loss of the 10, 13, 15, 16, 18, 19, 21 and 22 MeV proton energies in the primary targets lithium and tantalum were calculated by the Monte Carlo Simulation code SRIM-2008 [6]. The pressure inside the 6 m port was 8×10^{-8} torr, whereas it was atmospheric in the neutron activation zone.

Fig. 2.2 *The 6M irradiation set-up and target assemblies at BARC-TIFR Pelletron accelerator facility Mumbai.*

2.3 Target details

Two solid lithium and tantalum targets consisting of a Ta-Li layer on a 0.1 mm thick Ta were used in two irradiations for the production of the neutrons. In the first irradiation lithium foil of thickness 7.8 mg/cm^2 was placed between the front tantalum foil of thickness 3.2 mg/cm^2 and 0.1 mm thick. Similarly in the second irradiation the lithium foil of thickness 8 mg/cm^2 was placed between the front tantalum foil of thickness 4.0 mg/cm^2 and 0.1 mm thick. This 0.1 mm thick tantalum foil was used to stop the proton beam. In the present work, the natural samples were used for the measurement of neutron induced reaction cross section of different elements. The natural Selenium (Se), Vanadium (V), and Copper (Cu) in form of metal powder were used in the experiment. Chunk metal of Sb element was prepared into powder form using mortar and pestle, whereas a thin Rhodium (Rh) metal foil was used in the irradiation process. The isotopes of samples and the reference foil along with the purity and natural abundances are mentioned in Table 2.1.

Table 2.1 The stable isotopes of the samples and reference foil element along with the natural abundances [7].

Elements	Purity	Isotopes	Natural abundance (%)
Cu	(99.5 %)	^{63}Cu	69.15 (3)
		^{65}Cu	30.83 (3)
Sb	(99.89%)	^{121}Sb	57.38 (5)
		^{123}Sb	42.64 (5)
V	(99.95%)	^{51}V	99.75 (2)
Rh	(99.9%)	^{103}Rh	100
Se	(99.95%)	^{74}Se	0.89
		^{76}Se	9.36 (11)
		^{77}Se	7.63 (6)
		^{78}Se	23.77 (9)
		^{80}Se	49.61 (10)
		^{82}Se	8.73
Al	(99.99 %)	^{27}Al	100

Table 2.2 The masses of the samples Sb, V, Rh, Cu, Se and the reference foils Al used in each irradiation along with the thickness.

Sample irradiated	**Samples weight** (g)		**Thickness** (cm)	
Sb chunk metal Al metal foil	Sb	Al	Sb	Al
	0.601	0.0256	0.07	0.00948
	0.602	0.0259	0.07	0.00959
	0.600	0.0259	0.07	0.00959
V metal powder Al metal foil	V	Al	V	Al
	0.5014 (37)	0.0256 (13)	0.0618	0.01
	0.5011 (7)	0.0259 (17)	0.0618	0.01
	0.5006 (43)	0.0258 (3)	0.0617	0.01
Rh metal foil Al metal foil	Rh	Al	Rh	Al
	0.251	0.0309	0.0281	0.0114
	0.266	0.0313	0.0297	0.0116
Cu metal powder Al metal foil	Cu	Al	Cu	Al
	0.2152	0.0279	0.0319	0.0103
	0.2511	0.0309	0.0372	0.0114
	0.2464	0.0313	0.0365	0.0116
Se metal powder Al metal foil	Se	Al	Se	Al
	0.4343	0.0335	0.0802	0.0124
	0.4518	0.0279	0.0833	0.0103
	0.4314	0.0309	0.0796	0.0114
	0.4761	0.0313	0.0879	0.0116

A pelletizer was used to prepare a circular pellet of 12 mm diameter using metal powder. A high purity natural rhodium metallic foil samples of area 9 to 8 mm were taken. A rolling machine and pelletizer are shown in Fig. 2.3 for sample preparation. Along with the samples, a thin aluminium metal foil of area 1 cm^2 was placed with samples as a standard for normalization during the irradiation process. The sample used for neutron irradiation was wrapped in the 0.025 mm thick aluminium foil used to prevent radioactive contamination from each other. The masses of the samples and the reference foil that were used in irradiation are mentioned in Table 2.2.

Fig. 2.3 *Sample preparation rolling machine and pelletizer at target lab of BARC-TIFR facility.*

2.4 Neutron irradiations set-up

The irradiations on the samples were performed at the 14UD Pelletron Linac accelerator facility of Bhabha Atomic Research Centre and Tata Institute of Fundamental Research (BARC-TIFR) Mumbai, India. The 6M Irradiation setup of the accelerator facility was used for neutron production and activation. A schematic of the irradiation configuration is shown in Fig. 2.4. The neutron was produced via the ^{7}Li(p,n) reaction (E_{th}=1.88 MeV) using the proton of 10, 13, 15, 16, 18, 19, 21 and 22 MeV energies. The specially designed stem has a cavity made of Delran in which samples can be kept for neutron irradiation. These neutrons are produced in the forward direction and the entire assembly was isolated from the chamber. The samples and the reference foils were placed at 0^{o} with respect to the incident proton beam direction at 21 mm from the Ta-Li-Ta targets configuration. Two sets of irradiations were performed to measure the neutron induced reaction cross sections. The irradiation time for samples at different proton beam currents and energy are mentioned in Table 2.3.

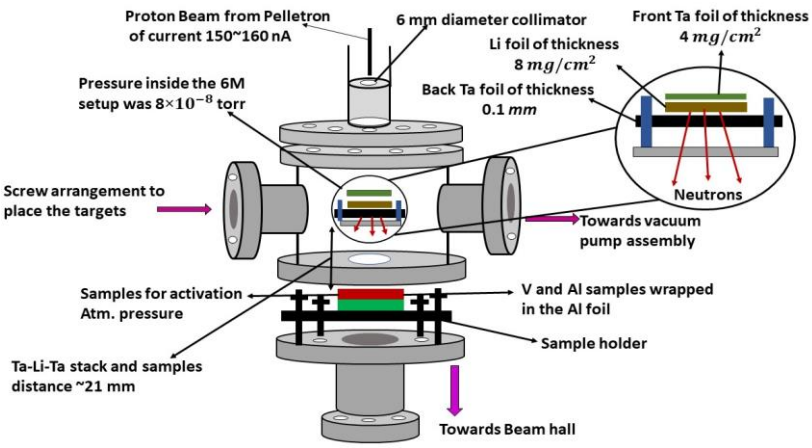

Fig. 2.4 *A schematic representation of the arrangement for neutron irradiation.*

Table 2.3 The experimental details concerning the proton energy and irradiation time.

Set	Proton Energy (MeV)	Proton beams current (nA)	Irradiation time (Sec)
1	13	120-160	37200
	16		28080
	19		21900
	22		18900
2	10	150-160	23400
	15		32700
	18		25200
	19		10680
	21		25200

2.5 HPGe detector set-up

High Purity Germanium (HPGe) detectors are semiconductor diodes having a p-i-n structure in which the intrinsic region is sensitive to ionizing radiation, particularly X-rays and γ-rays. All semiconductor detectors are used in reverse bias because the thickness of the depletion region is larger in reverse bias. There are three types of reaction which happen in germanium semiconductors (i) Photoelectric effect (ii) Compton scattering and (iii) Pair production. The photoelectric effect is the primary process by which photons interact with materials with high atomic numbers at low energy. Compton scattering is the dominating interaction at intermediate energies in low atomic number materials. The last pair production is the mechanism of photon detection at very high energy. The latter two processes dominate

when the energy of the injection photon is greater than 1 MeV [8-9]. There are two kinds of HPGe detectors, n-type, and p-type. The coaxial p-type HPGe detector manufactured by BSI was used in the present work for the activity measurements of the samples, whose model is GCD-40190. These lead shielded HPGe detectors were used for the offline measurement of the induced activity of the irradiated samples. The HPGe detector was connected to the computer data acquisition system via a separate analogue-to-digital converter (ADC). A block diagram of the γ-ray spectrometry set-up is shown in Fig. 2.5. This is assembled with a pre-amplifier high voltage power supply, linear amplifier, and a multichannel analyzer with facilities for storage and display of the experimental data. A brief description of each unit is given below. The same electrical circuit for all A.C. power to the system was used to avoid ground loops. The bias supply and amplifier were located at opposite ends of the bin to minimize cross talk between them [10].

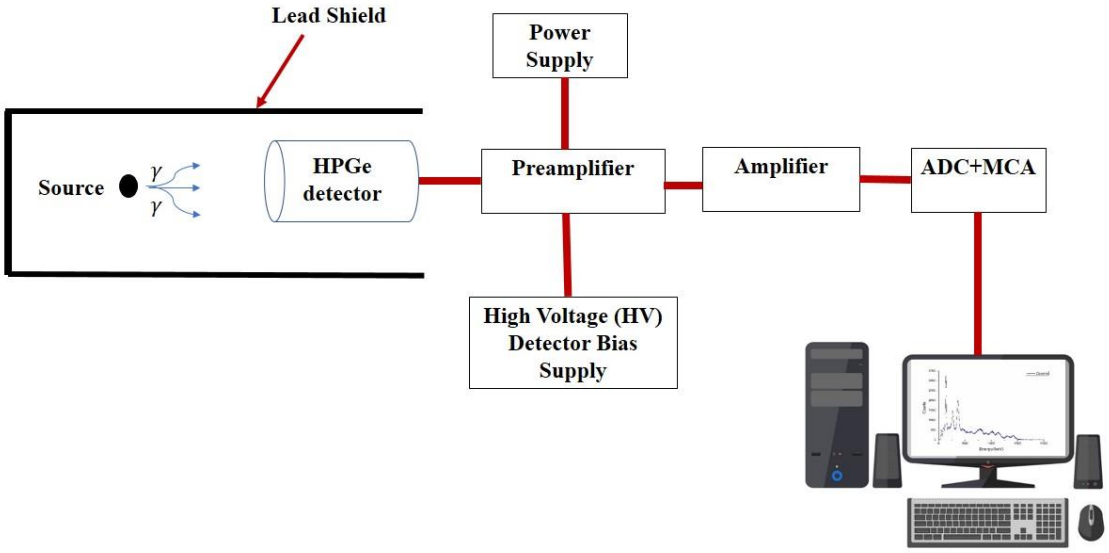

Fig. 2.5 *A schematic block diagram of gamma spectrometry set-up at the BARC-TIFR facility.*

Pre-amplifier: the charge liberated by the incident radiation is sufficient to produce a large signal pulse in detectors. In semiconductor detectors, the charge is so small that it is impossible to deal with the signal pulses without any intermediate amplification step. Therefore, the first element in a signal processing chain is a pre-amplifier working as an interface between the detector and the pulse processing electronics. The pre-amplifier is kept

as close to the detector as possible to minimize the capacitive loading on the detector by avoiding long interconnecting cables between the detector and the pre-amplifier. Thus, a maximum peak to noise ratio can be achieved by quickly terminating the capacitance. A Field Effect Transistor (FET) which serves as the first stage of the amplifier is cooled to liquid nitrogen temperature for its proper function; for this reason the pre-amplifier is kept in thermal contact with the cryostat housing the detector. The detector HPGe is associated with charge sensitive pre-amplifiers. These pre-amplifiers are preferred for most spectroscopy applications. The pre-amplifier converts the ionization charge developed in the detector during each absorbed nuclear event to a step function pulse output whose amplitude is proportional to the total charge accumulated in that event. The sensitivity (or gain) is generally expressed in millivolts per MeV of energy deposited in a given detector material. The charge Q released by the detector is a function of the particle energy and the detector material and is provided by

$$Q = E * e \times 10^6/\epsilon$$

E is the energy of incident radiation in MeV, e is the charge of the electron and ϵ is the amount of energy required to produce an electron-hole pair in the detector (approximate value for Ge is 2.96 eV at 77° K). Thus, any change in the input capacitance has no appreciable effect on the output voltage in this pre-amplifier class.

Detector bias supply: The detector involved in the present work requires an external high voltage (HV) for its proper operation. This voltage is conventionally called "detector bias", and the units used for this purpose are often called detector bias supply. An HV supplier is linked to the HPGe detector. This bias voltage sweeps out the electron hole pairs from the detector which are collected by the preamplifier. It is crucial to confirm the polarities of the HV supplier and the detector are the same. The detector can stable with each increase in voltage since the HV supplier is also connected at 0 V and raised gradually to the desired voltage.

Amplifier: Pulse shaping and amplitude gain are the two primary functions of the linear amplifier. The output signal obtained from a pre-amplifier is fed to an amplifier to amplify the signal further and shape the signals to optimize spectrometer performance. An amplifier's essential requirement is to have an optimum pulse shape, enhance the signal-to-noise ratio, and make the amplification independent of variations in input pulse rise times. If the product of input amplitude and gain exceeds the maximum design output amplitude, the amplifier

output pulse will saturate and produce a distorted pulse with a flat top at that amplitude; linear amplification will be realized only for those pulses that are short of this saturation level. Hence, an amplifier with a built-in pile-up rejecter and an automatic baseline restorer is employed for the present work to achieve exceptionally stable performance.

Analogue-to-Digital Converter (ADC): ADC is a data converter which converts continuously changing analogue signals to discrete digital signals. This digital circuit works with the binary signal which has two discrete states, a logic "1" (HIGH) or a logic "0" (LOW).

Multichannel analyzer: The multichannel pulse height analyzer (MCA) is an instrument developed to examine each pulse coming from the main amplifier and determine into which size category it should fit. The pulse height is proportional to the gamma-ray energy deposited in the detector. The MCA keeps a record of its memory of how many pulses of each size it has found. The MCA presents the number of counts in each channel, in effect in a histogram. The number of channels available depends upon the MCA but usually ranges from 1024 to 8182. Modern MCA is special purpose computer whose memory addresses can be programmed to correspond to increment to voltage. Each time a detector produces an output signal, the signal's amplitude is converted to a pulse train by the computer. These pulses are counted on an address scalar in the computer memory. The sum of the pulses produced by a given input signal equals the data address. The address (proportional to the signal amplitude) is selected and a count of one is added to the content of the memory at that address. The next signal from the detector is digitized, and the address proportional to the amplitude of the detected signal is selected. A count of one is added to the memory at that address. The process continues for a duration determined by the experimenter, and an energy distribution spectrum is recorded. This process is called pulse height analysis.

Data acquisition and spectrum analysis software:

The full gamma spectrum analysis was done with Genie 2000 basic spectroscopy software. It is software for both spectrum analysis and data acquisition in gamma spectroscopy. This software offers a simple Graphical User Interface (GUI) for Gamma Spectrum Analysis. It offers spectrum analysis in both online and offline modes [11]. Furthermore, a Windows based software program MAESTRO was also used for the offline analysis of the γ-ray spectrum. This software includes functions that will be useful for

spectrum analysis, these functions are Region of Interest (ROI), gaussian fits, peak finders, the sum of counts and calibration [12].

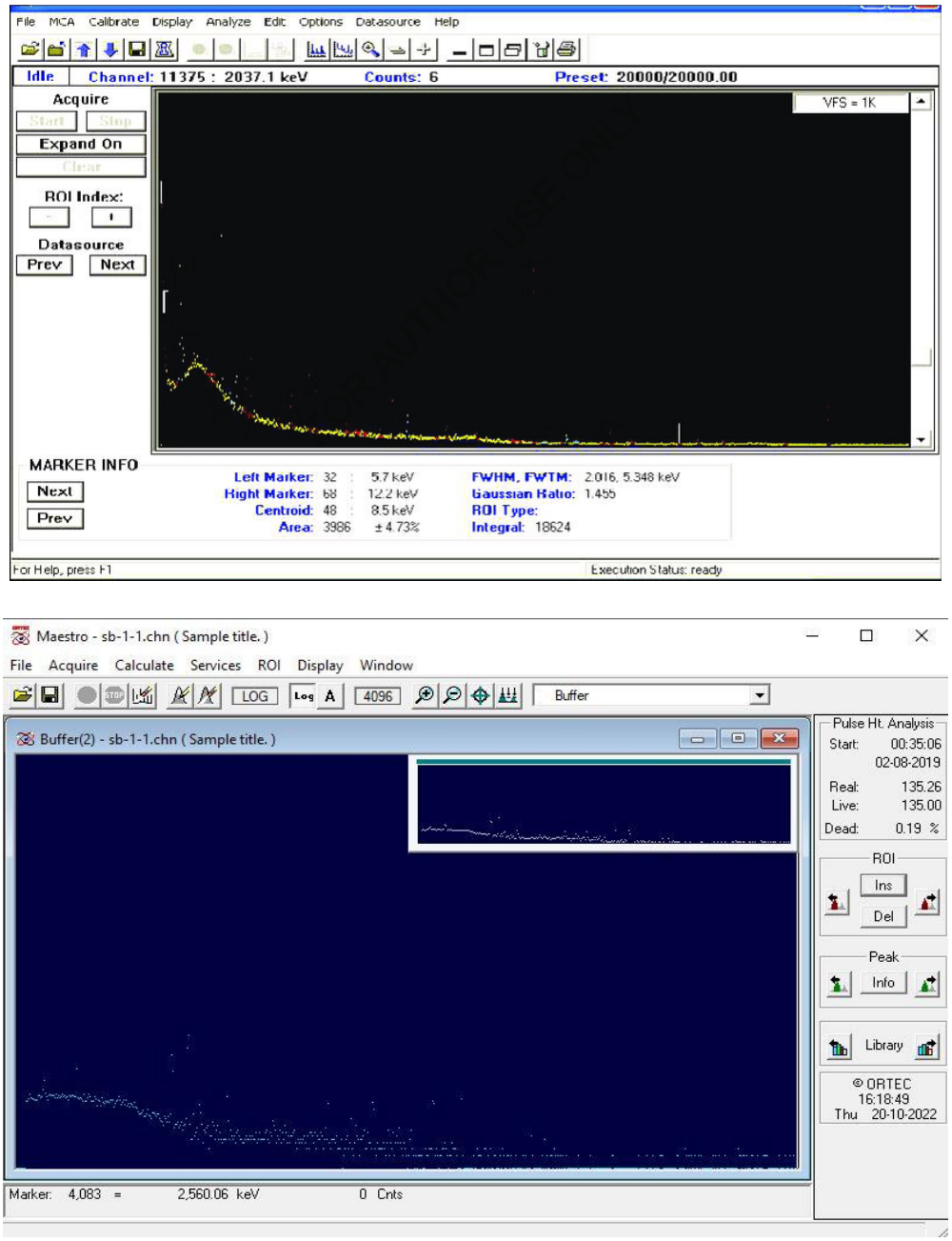

Fig. 2.6 *The GUI of the Genie and MAESTRO Interface software.*

2.6 Off-line γ-ray spectrometry method

After the end of the irradiation, the induced activity of the radioactive source was measured using the off-line γ-ray spectrometry method using the pre-calibrated HPGe detector. This method is the quantitative study of the energy spectra of the radioactive source.

The HPGe detector and electronic devices were the main components of the γ-ray spectrometry. All radioactive sources emitted γ-ray of different energies and intensities. The setup for the offline γ-ray spectrometry method is shown in Fig. 2.7. These γ-ray is absorbed and converted into a voltage signal by the detector and the detected γ-ray energy is proportional to the voltage signal. This quantitative method is only helpful to measure the reaction cross section for those nuclei which have sufficient half-life to record the γ-ray spectrum of the sample. This off-line γ-ray spectrometry is helpful for counting sample activity according to the half-life time, whereas this method is not suitable for shorter half-life nuclei. All samples are placed at a suitable distance for counting in front of the lead shield HPGe detector [13].

Fig. 2.7 *Off-line γ-ray spectrometry method setup along with lead shield HPGe detector.*

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